COMBINED INVESTIGATION OF EDDY CURRENT AND ULTRASONIC TECHNIQUES FOR COMPOSITE MATERIALS NDE

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INTRODUCTION

Advanced composites are not without trade-offs. Their increased designability brings an increase in the complexity of their internal geometry and, as a result, an increase in the number of failure modes associated with a defect. When two or more isotropic materials are combined in a composite, the isotropic material failure modes may also combine. In a laminate, matrix delamination, cracking and crazing, and voids and porosity, will often combine with fiber breakage, shattering, waviness, and separation to bring about ultimate structural failure. This combining of failure modes can result in defect boundaries of different sizes, corresponding to the failure of each structural component. For example, impacting a graphite/epoxy (gr/ep) laminate locally alters both fibers and matrix, causing cracking, delaminations, fiber displacement and shattering. While normal mode ultrasonics are affected by all these alterations, this technology is more matrix-sensitive than fiber-sensitive. On the other hand, the conductive fibers allow eddy current imaging to isolate any fiber effects. Thus, the two techniques are complementary and yield a more complete picture of the composite damage. Therefore, gr/ep maintainability criteria should require the coordinated use of both EC and UT technologies (with a possible third technology to isolate matrix cracking). Consequently, more than one NDE technique is needed to completely investigate composite structural integrity.

This paper discusses a dual-technology NDE (eddy current (EC) and ultrasonics (UT)) study of graphite/epoxy (gr/ep) laminate samples. Eddy current and ultrasonic raster (C-scan) imaging were used together to characterize the effects of mechanical impact damage,

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high temperature thermal damage and various types of inserts in gr/ep laminate samples of various stacking sequences.

EXPERIMENTS

To obtain a fairly wide diversity of defects, three distinct sets of samples were studied. The first set was part of an NDE study with the Mc Donnell-Douglas Aerospace Division, St. Louis, Mo., and the US Navy. They contributed twelve 15.2 x 16.5 cm^2 (6.0 x 6.5 in^2), 16 ply, [0]8s, unidirectional, AS4/977-3, laminates under-coated with Mil-P-85582 primer. One side was top-coated with MMS-420 gloss white paint and the other coated with color #36320 flat grey paint. The white sides were thermally exposed with a 20.3 x 15.2 cm^2 (8.0 x 6.0 in^2) heat blanket, while an insulating blanket reduced heat transfer from the grey sides. It is not known if temperatures were actually kept uniform over the entire surface of each panels, as temperatures were only monitored at the centroids.

Boeing Aircraft supplied a 48 ply, gr/ep sample with a periodically repeated fiber orientation of +45°, 90°, -45° and 0°. The sample, (overall dimensions of 30 x 45 cm^2 (12 x 18 in^2), contained a series of 1.27 cm^2 (0.5 in^2) non-conducting inserts, placed at different ply levels.

Finally, an impacted gr/ep sample, with no visible damage was investigated. The sample was cross-ply, several plies thick with overall dimensions of 10 x 25 x 0.3 cm^3 (4 x 10 x 0.125 in^3). Further documentation on the panel is limited.

Two ultrasonic techniques were used to study the samples. The first was a standard pulse-echo attenuation C-scan, iterated to optimize the resulting ultrasonic image. Here optimizing means achieving the finest resolution of detectable features with the greatest pixel value difference between them for maximum image contrast. This was accomplished by confining the scan area to well within specimen boundaries, then maximizing the effective dynamic range, to produce the widest normalized value scale, and having the maximum number of peak amplitudes fall within that range such that amplitude response fluctuations and, therefore, acquired pixel value differences, were also maximized [1]. A value scale, ranging from 0 - 1254, was created by using two receivers set for maximum linear gain. A spectrum analyzer was then used to check for distortion from repeated amplification.

Lamb waves were also used for investigating the effect of thermal-damage on the their phase velocity [2]. Lamb wave phase velocity is sensitive to the density of the material, the elastic constant in the propagation direction and Poisson's ratios for strains normal and parallel to the propagation direction [3]. The initial test setup consisted of pin-ducers set at intervals to register time of flight, allowing for group velocity measurement. An improved setup used finite-sized transducers and a pulse phase-locked loop to take data that will be analyzed at a later date.

Eddy current scans were also performed to isolate fiber damage in the samples. A standard eddy current impedance plane instrument equiped with a with a 6 mm (0.25 inch) diameter spring loaded, ferrite core probe (2.5-6 MHz, the frequency range needed for three standard depths of penetration to fall within the thickness of the samples) was used for data acquisition. On the impacted and inserted samples, the tester was balanced on a "good" part of the sample set for maximum horizontal (real) component of the lift-off signal vector. This effectively separated the resistive component (horizontal) from the reactive component (vertical) which were recorded separately as the probe was mechanically scanned over the sample surfaces. An unexposed control panel was used for probe adjustments for the thermal effects scans.

RESULTS AND DISCUSSION

Fig. 1 shows the optimized ultrasonic attenuation image for the three most thermally exposed panels, compared with the unexposed control panel. The three panels were subjected to a temperature of 537°C (1000°F) for a period of 3 minutes before NDE. Note the "hot-spots", areas of greatest apparent thermal effect, with sharp boundaries. Outside these hotspots, the samples appear very similar to the control sample. Note, also, similarities in the shape and location of the hotspots. Hotspot shape differences seem to correlate with differences in the net absorbed thermal energy due to variations in the time/temperature profile, but this effect will not be considered here. (Time/temperature data is available on request). All the UT attenuation images show little thermal degradation outside the hot-spot boundaries. Inside the boundaries, there is a narrow transition region surrounding a region of randomly scattered pixel values (the cause of which is believed to be porosity due to pyrolysis of the epoxy matrix). UT attenuation slope plotted vs frequency gave curve shapes identical to the control sample when computed outside a hotspot. The curve shapes differ radically for curves from inside the hotspots.

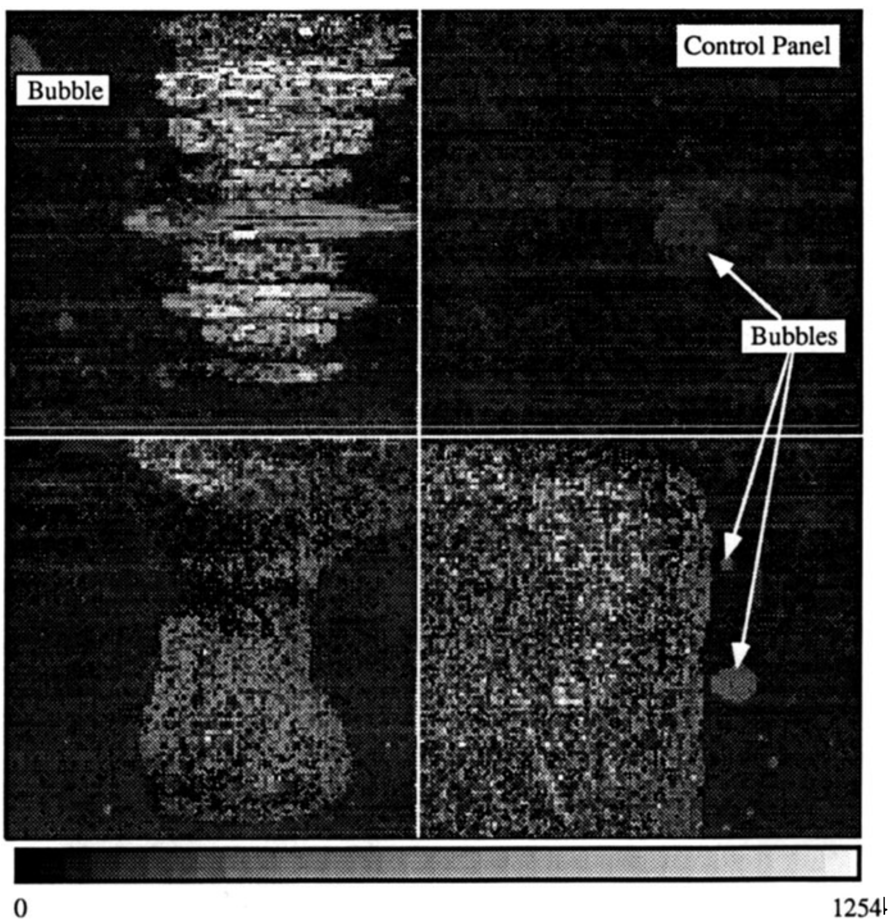


Fig. 1. Ultrasonic attenuation image (Normal mode, planform orientation) of three thermal-damaged composite panels along with an unexposed control panel.

The Lamb wave results are provided in Fig. 2 below. Although the results are preliminary (note error bars), this figure shows a definite decrease in overall lambwave velocity as a function of final sample temperature. At lower temperatures, the data is not as well correlated, this is due to sample anisotropy and uncertainty in the group velocity measurements. Data from an improved lambwave setup will be featured in a later study.

The eddy current images were taken at probe frequencies of 4.0 MHz, 4.5 MHz, 5.0 MHz, and 6.0 MHz. Typical results are shown in Fig. 3 below. The images are of impedance measurements from the undamaged control panel and portions of the same three thermal-

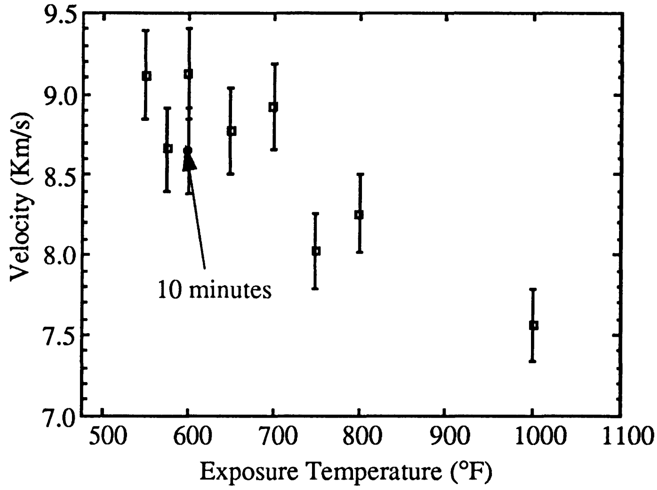


Fig. 2. Lamb wave velocity results for thermal-damaged samples. The exposure temperature was maintained for an average of 3 minutes except where noted.

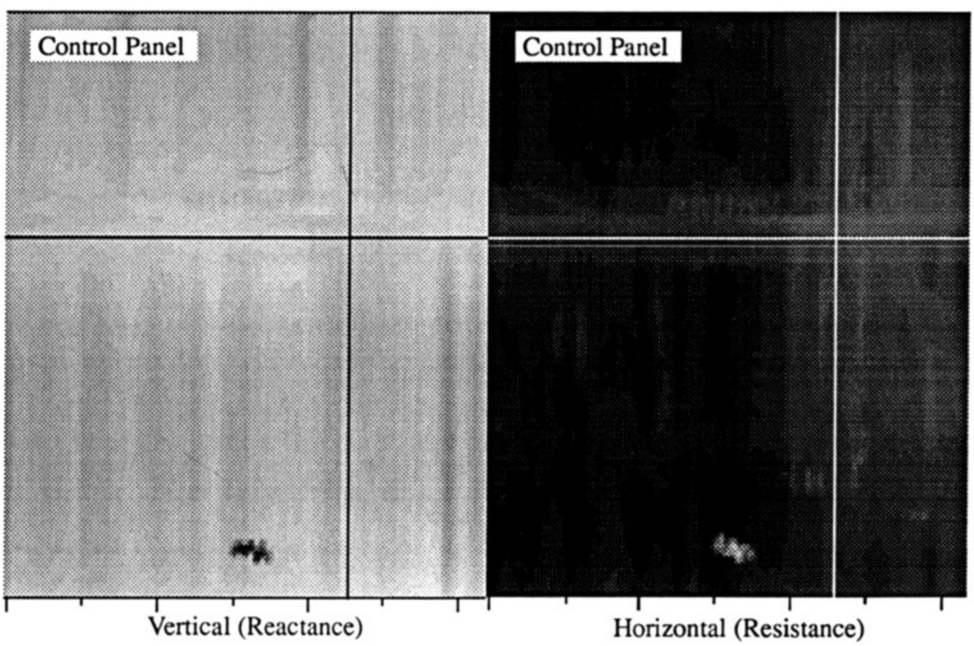


Fig. 3. Eddy current impedance images (4.0 MHz) of a portion of four composite panels. The panel boundaries have been enhanced with added lines.

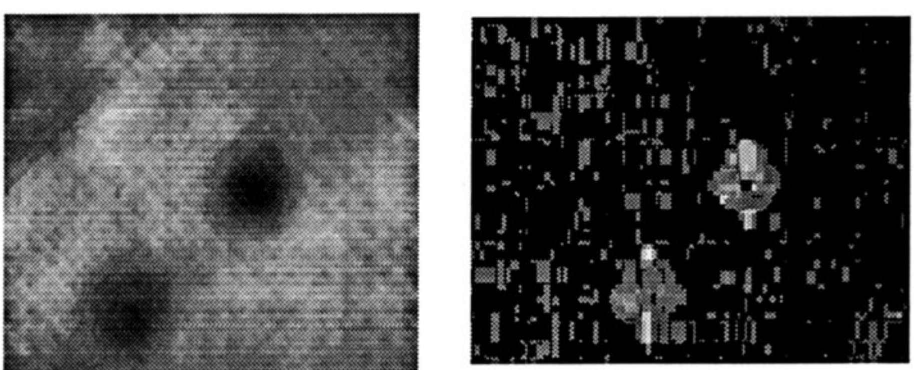
damaged panels UT-imaged in Fig. 1. The impedance results are displayed using images of the horizontal (changes in horizontal values coincide with changes in lift-off corresponding to resistance changes) and vertical images from the impedance plane values. The images do not have any features not attributable to changes in lift-off. Variations in the Resistance plot can be accounted for by surface roughness changes, and wear tape at sample boundaries. Since the only electrically conductive material in the panels are the graphite fibers, it is reasonable to assume that the fibers are not appreciably altered.

Fig. 4 illustrates some of the benefits of coordinating the two technologies to evaluate an impacted gr/ep laminate. The UT attenuation scan shows not only the delamination patterns and their shapes due to stacking sequence, but it also gives evidence of random scatterers like voids and porosity. On the other hand, the impedance image (vertical component shown), made from the side opposite of the impact, more clearly shows fiber orientation and a significant impedance change due to fiber displacement and, possibly, shattering. It is important to note there is little similarity in the shapes of the eddy current impact images compared to the UT images. This can have adverse implications if one plans to use only one imaging technology to map defect boundaries.

In Fig. 5 we show eddy current images of non-conducting inserts in a gr/ep composite panel. This is significant asit shows a sensitivity in the EC response to delaminations and not just to broken fibers. Surface roughness measurements of the same specimen show significant variations corresponding to the locations of the non-conducting inserts. A line scan of the variations is shown in Fig. 6. The changes in the eddy current signal due to the inserts are attributed to fiber displacement. This effect is similar to thickness change variations observed using eddy currents in isotropic conductors. This result should be considered when interpreting the images of delamination patterns, particularly from impact, a major cause of fiber displacement.

SUMMARY

The objective of this paper was to show the need for coordinated use of two or more NDE technologies to detect and asses composite defects. For the thermal-damaged panels, UT studies indicate that the thermal effects are confined to the hot-spots with no detectable degradation outside those regions. This result was partially validated by the Lamb wave analysis. There is an apparent decrease in the lamb wave velocity as the maximum sustained temperature is increased, however, these results are considered tentative as indicated by the



Eddy current image Ultrasonic image

Fig. 4. Impact damaged composite sample imaged using ultrasonic attenuation and eddy current impedance measurements. The ultrasonic data was taken at 5.86 MHz and the EC results were performed at 4.0 MHz.

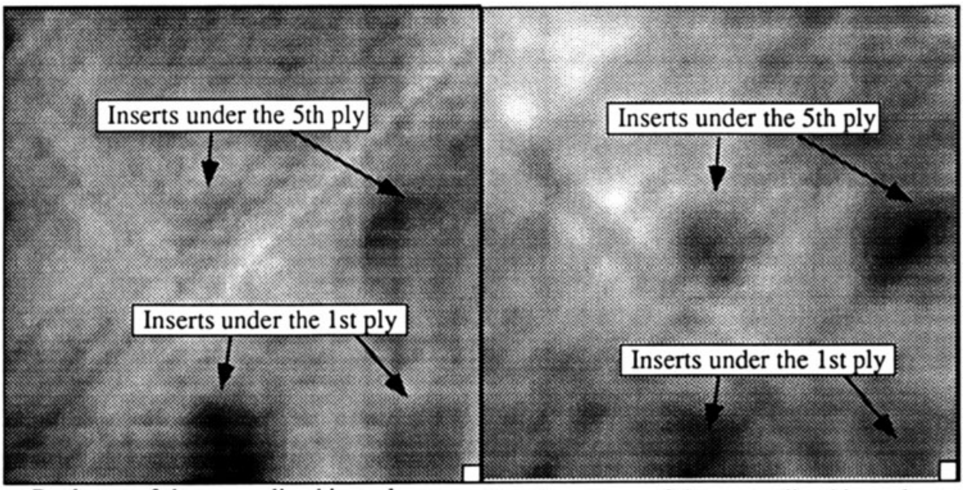


Fig. 5. Image of the probe impedance of a 2.5MHz eddy current probe scanned over a composite sample containing non-conductive inserts. The scan region is 7.6 cm^2 (3 in^2).

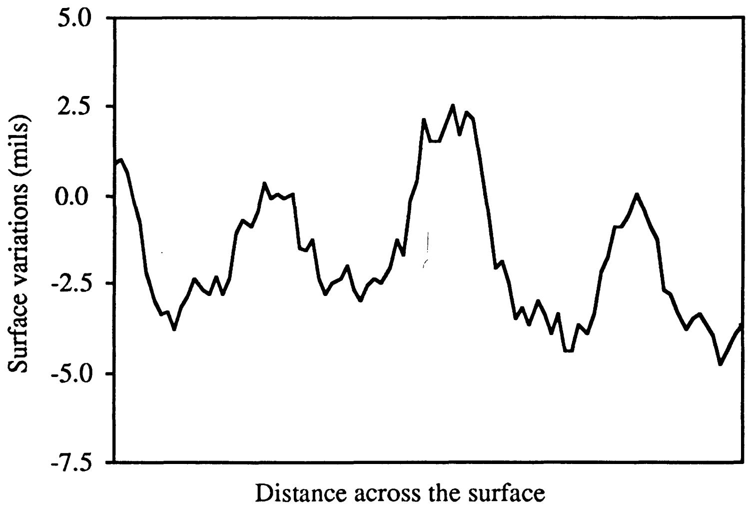


Fig. 6. Surface roughness variations along a line containing three inserts located at the fifth ply in the composite sample.

error bars in figure 2. The eddy current results seem to indicate that the sample degradation is limited to the epoxy matrix and does not significantly effect the fibers. The only indications observed by the EC inspection were resistive due to lift-off changes from the thermal-roughening of the pain at the hotspots and the adhesive tape securing the panels together. The reactive images are virtually featureless with the exception of indications due to the reference markers (metal tabs), edge effects, and where the liftoff response was non-linear. These conclusions will be tested further in the near future. Uncoated panels with larger planforms will be requested for better Lamb wave performance and for EC/UT responses unaffected by coatings.

The impact and insert study isolated the EC indications of delamination so they can be correlated with ultrasonic data. An important result is the different boundary shape shown by EC imaging in comparison to UT attenuation imaging.

Composite damage occurs in a variety of modes. The interaction of damage modes can conceal their individual signatures from a single NDE technology. Therefore, accurate assessment is more likely when two or more NDE technologies are used to sort them out. Although this study was limited to gr/ep laminates, the multiple NDE technology approach can be adapted to other composite types including those requiring different NDE technology combinations.

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